Ionospheric Variability's Impact on HF Propagation: Insights from Grape V1 Doppler Residuals and PHaRLAP Ray-tracing

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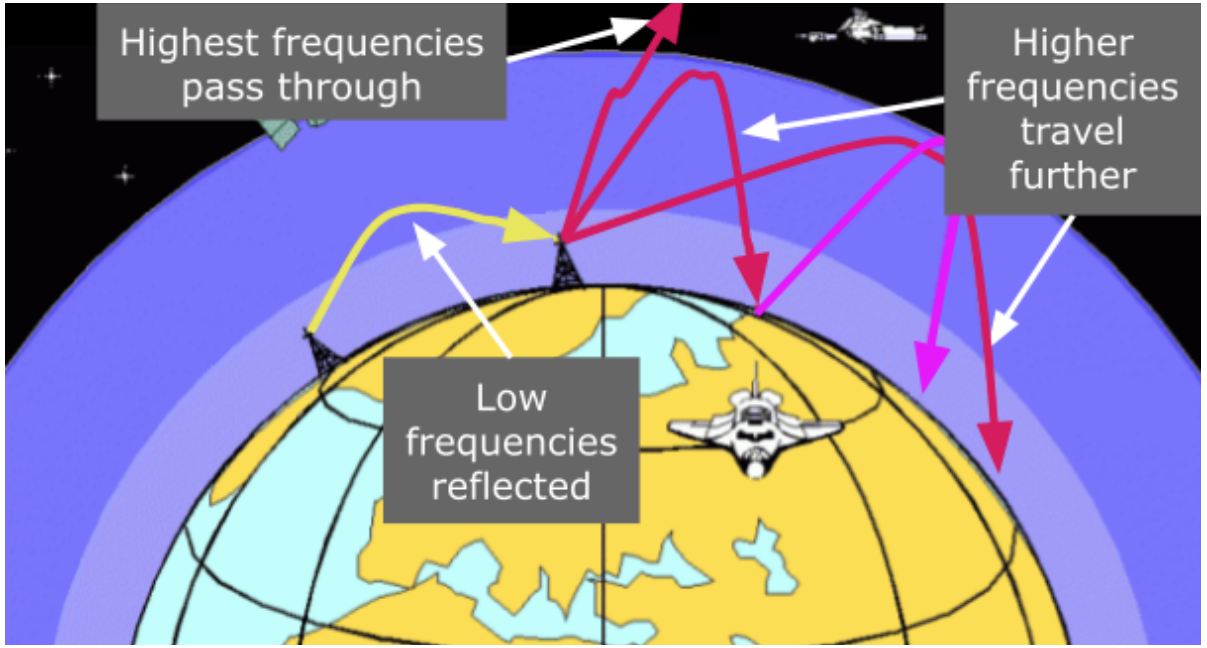
High Frequency Radio Signals

- **HF (3-30 MHz)** skywave signals used in global radio communications
- Doppler residuals of these signals can be used to remotely sense **bottom side ionosphere**
  - Fluctuations in TEC and electron density
- A **Grape V1** PSWS node can monitor a single HF channel with continuous time resolution along a single path (Collins[3] et. al.)



Adapted from: Space Weather Prediction Center[1]

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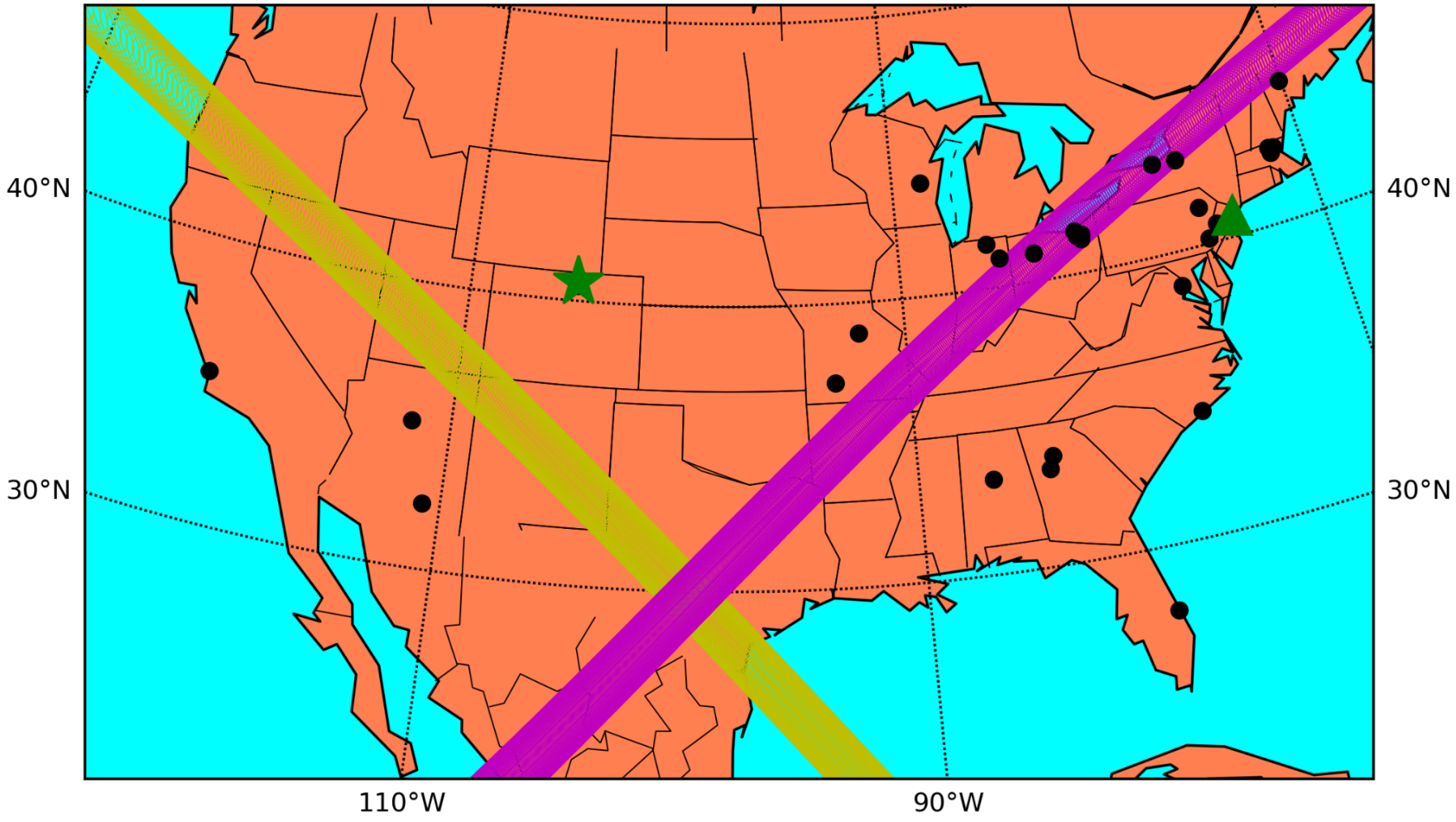
Grape V1 Data Contributions (2019 - 2023)



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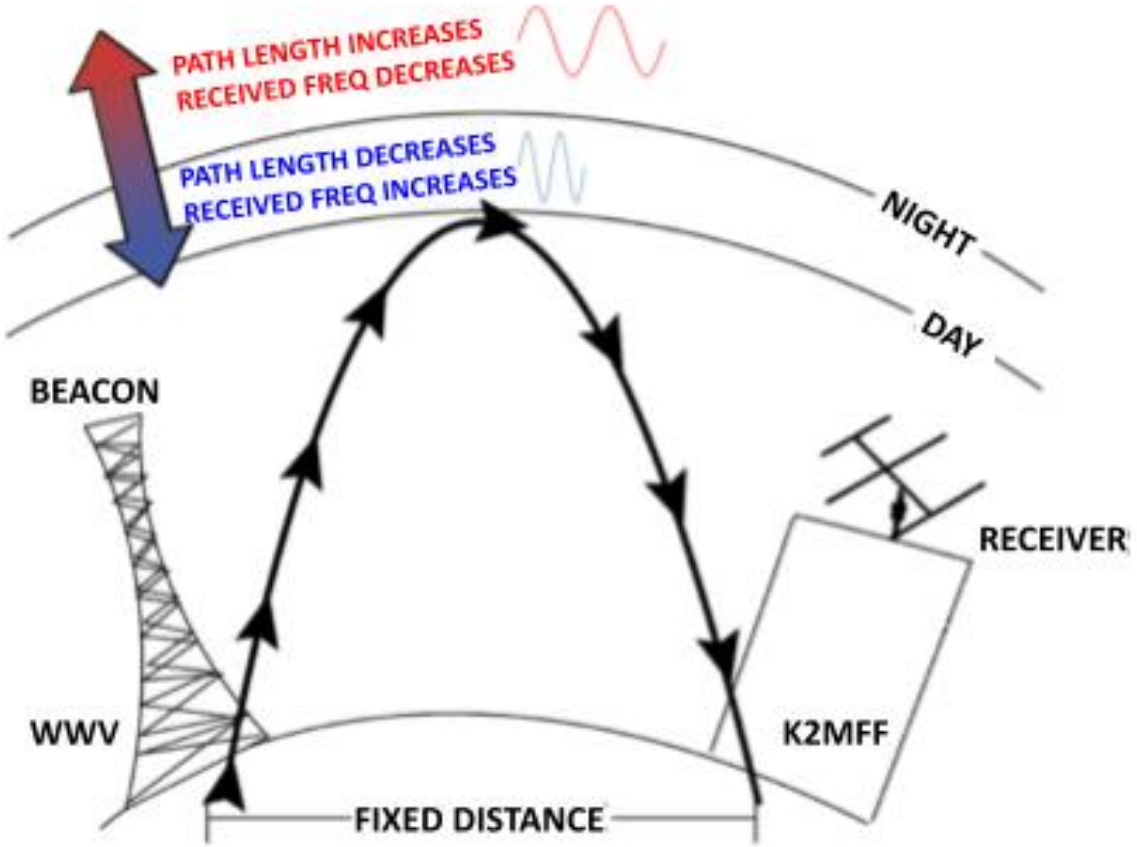
Setup

- Grape V1 **low-IF receiver** (K2MFF) installed with a 30m inverted vee antenna tuned to 10MHz at NJIT in Newark, New Jersey
- 10MHz signal is generated by the NIST radio station **WWV** in **Fort Collins, Colorado**
  - GNSS disciplined oscillator produces an extremely stable signal
- **Difference** between peak received signal and 10MHz taken as ‘doppler residual’
  - Sampling rate of 1Hz



Adapted from: Collins et al.[2]

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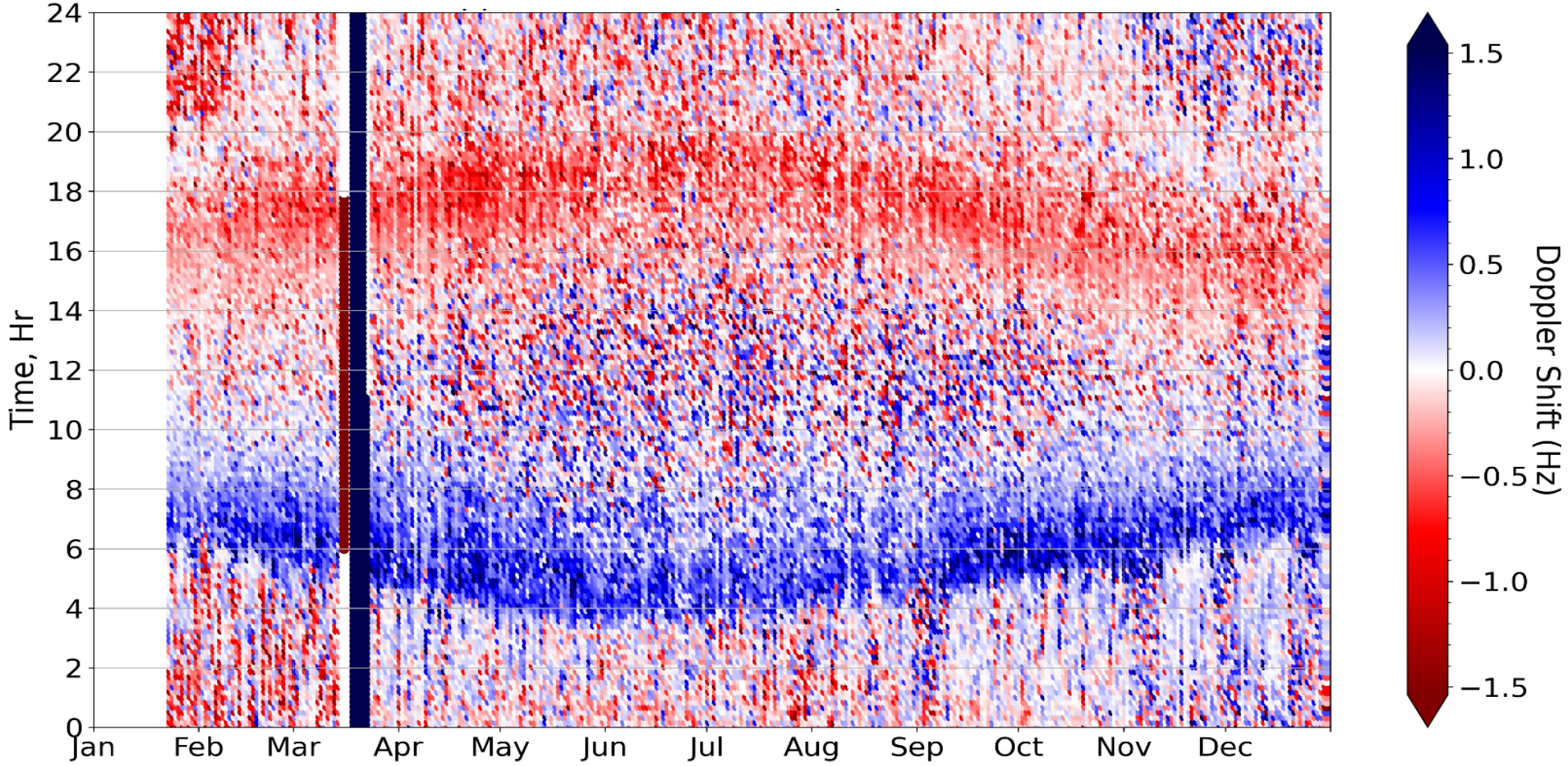
Methodology

Aggregate Data

2022 Doppler Residuals Above 1-hop Illinois Midpoint (41.75, -89.61)



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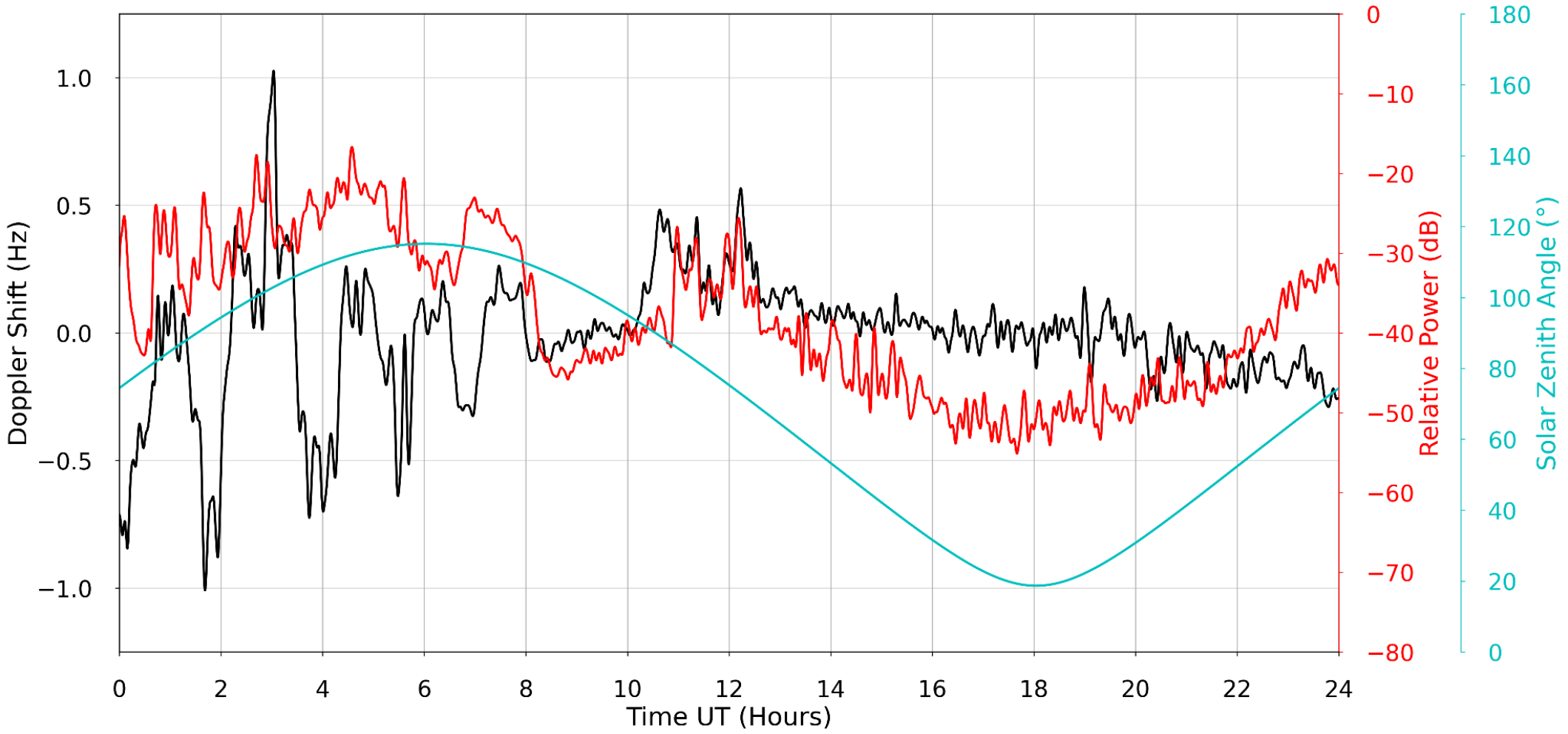
Methodology

24-Hour Data

Doppler Residual Plot for July 1, 2021
10 MHz from WWV → K2MFF



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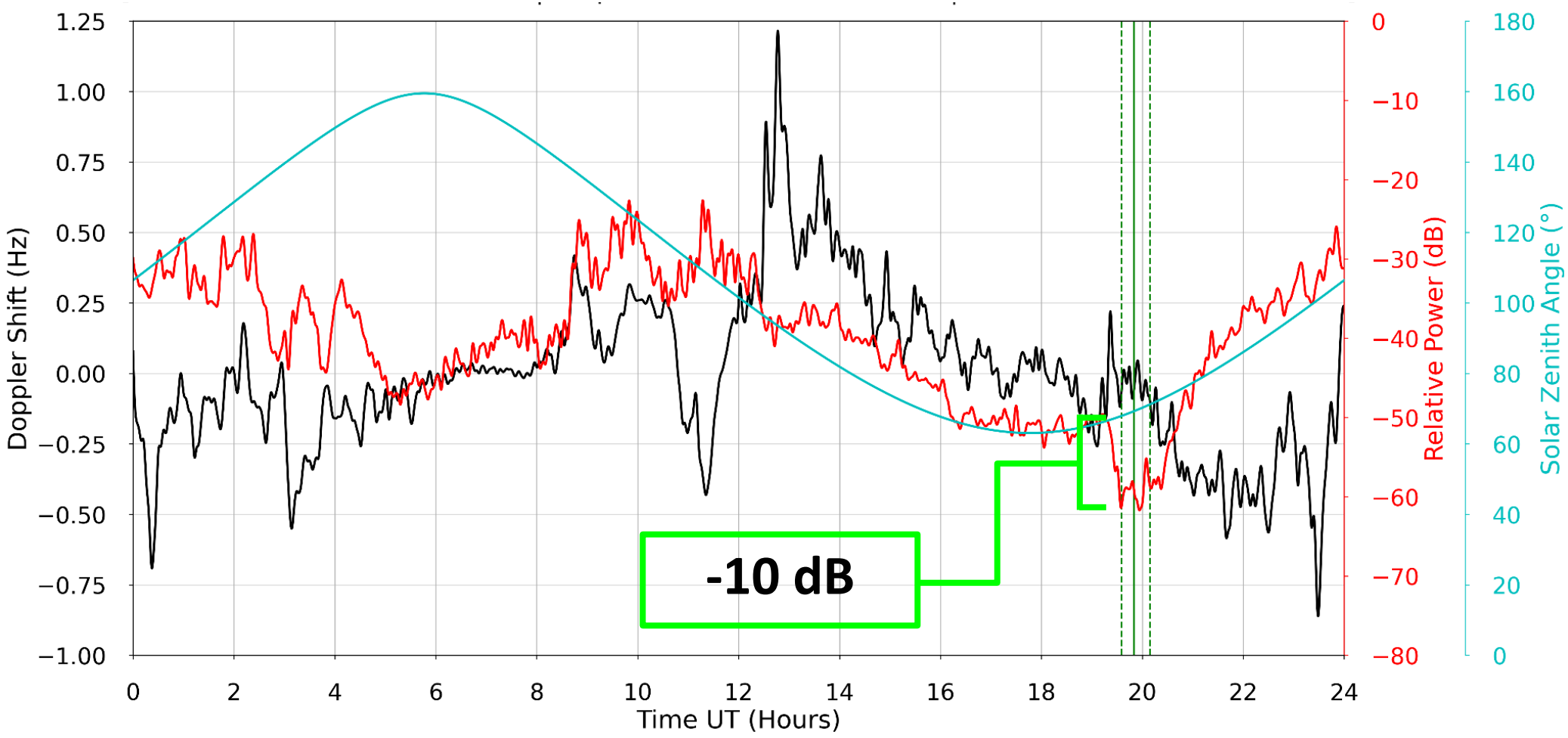
Case Studies

2023 Solar Flare

November 11, 2023 Traces + Maximum HF Absorption Period



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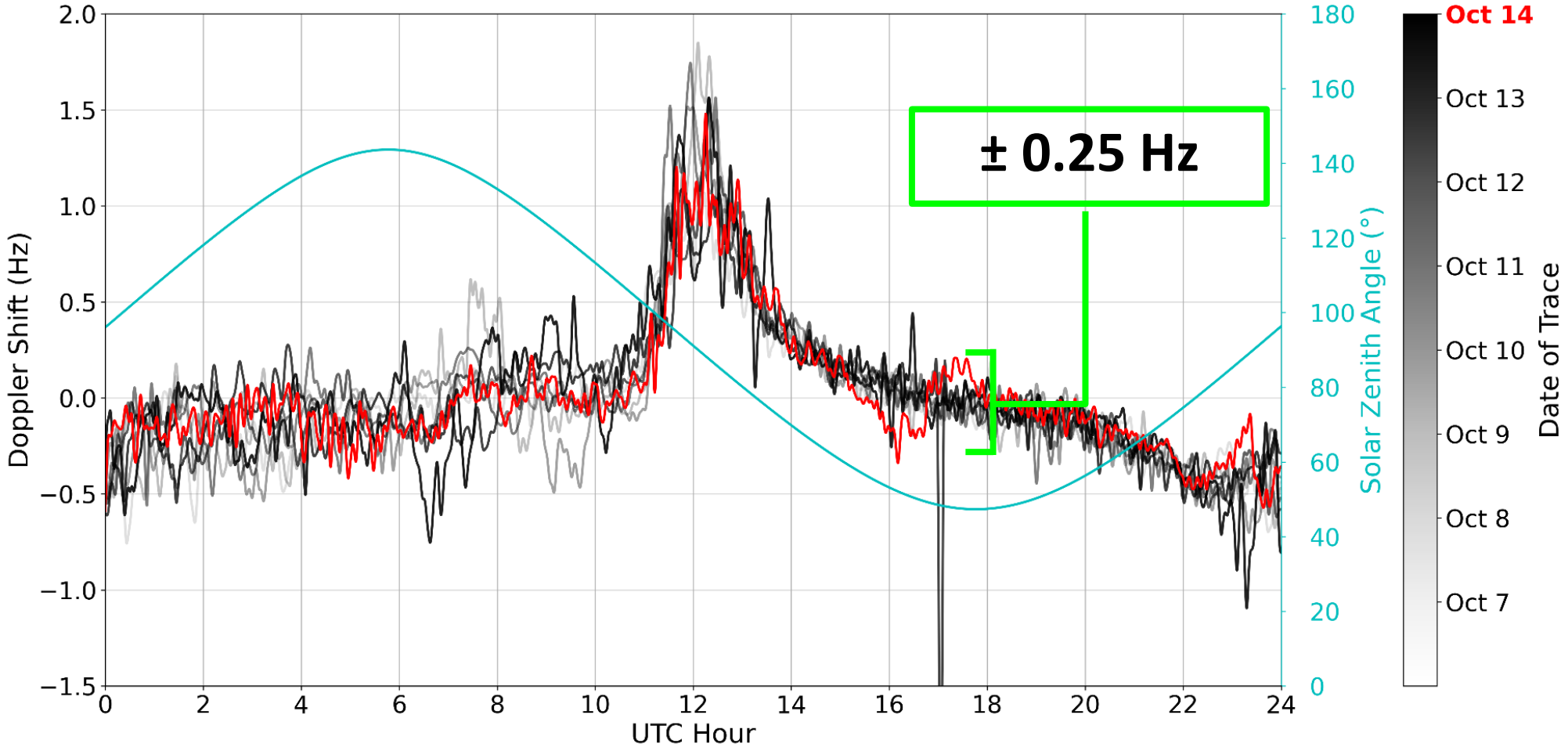
Case Studies

2023 Annular Eclipse

Doppler Residuals of 7 Preceding Days + October 14, 2023 Trace



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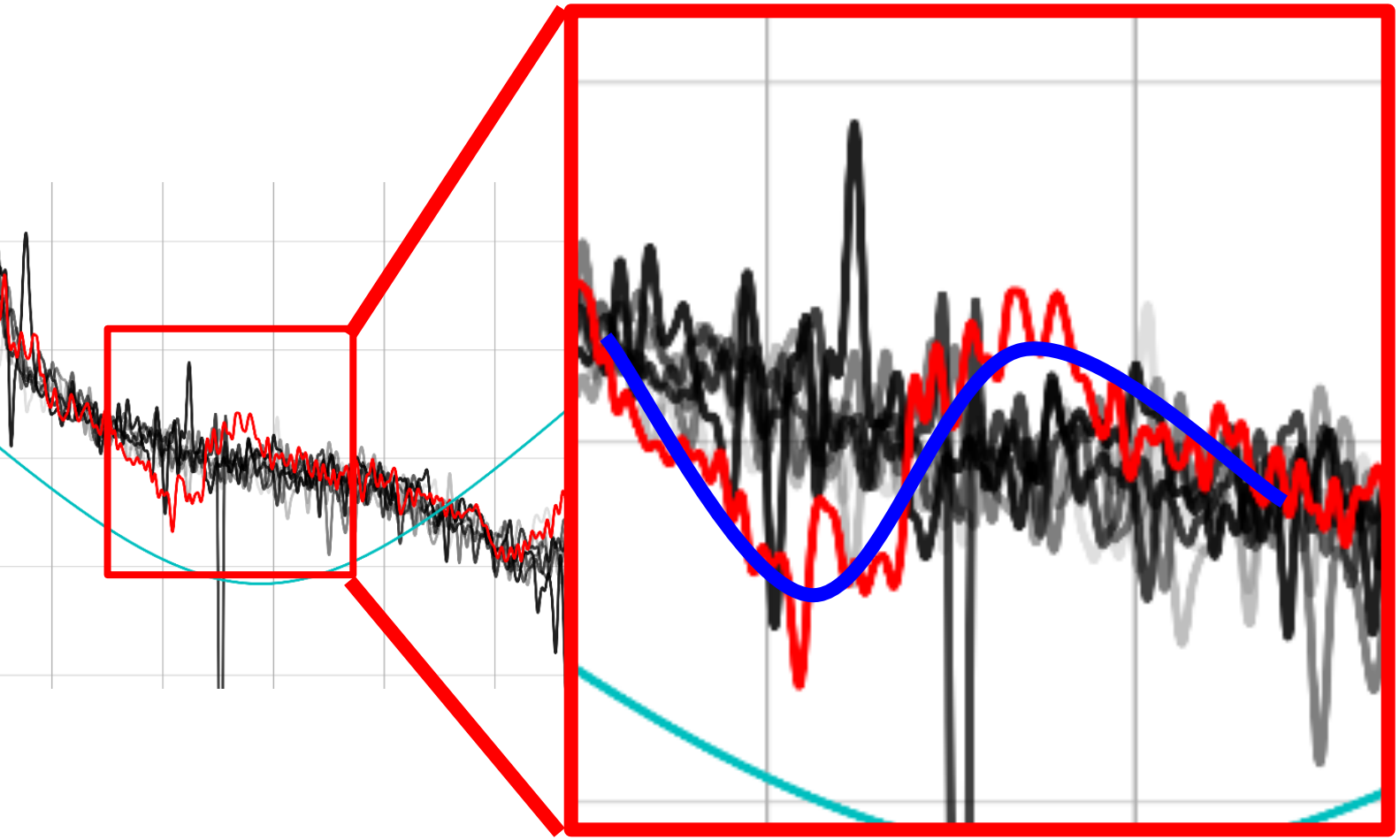
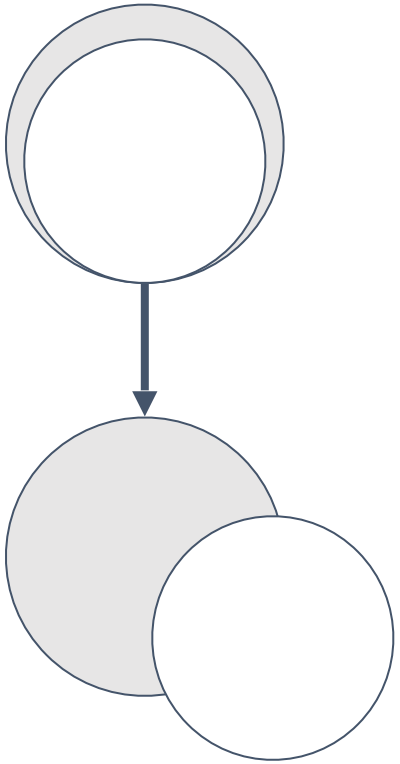
Case Studies

2023 Annular Eclipse

“S-curve” in Doppler Residuals for October 14, 2023 Trace





Deionization

Reionization

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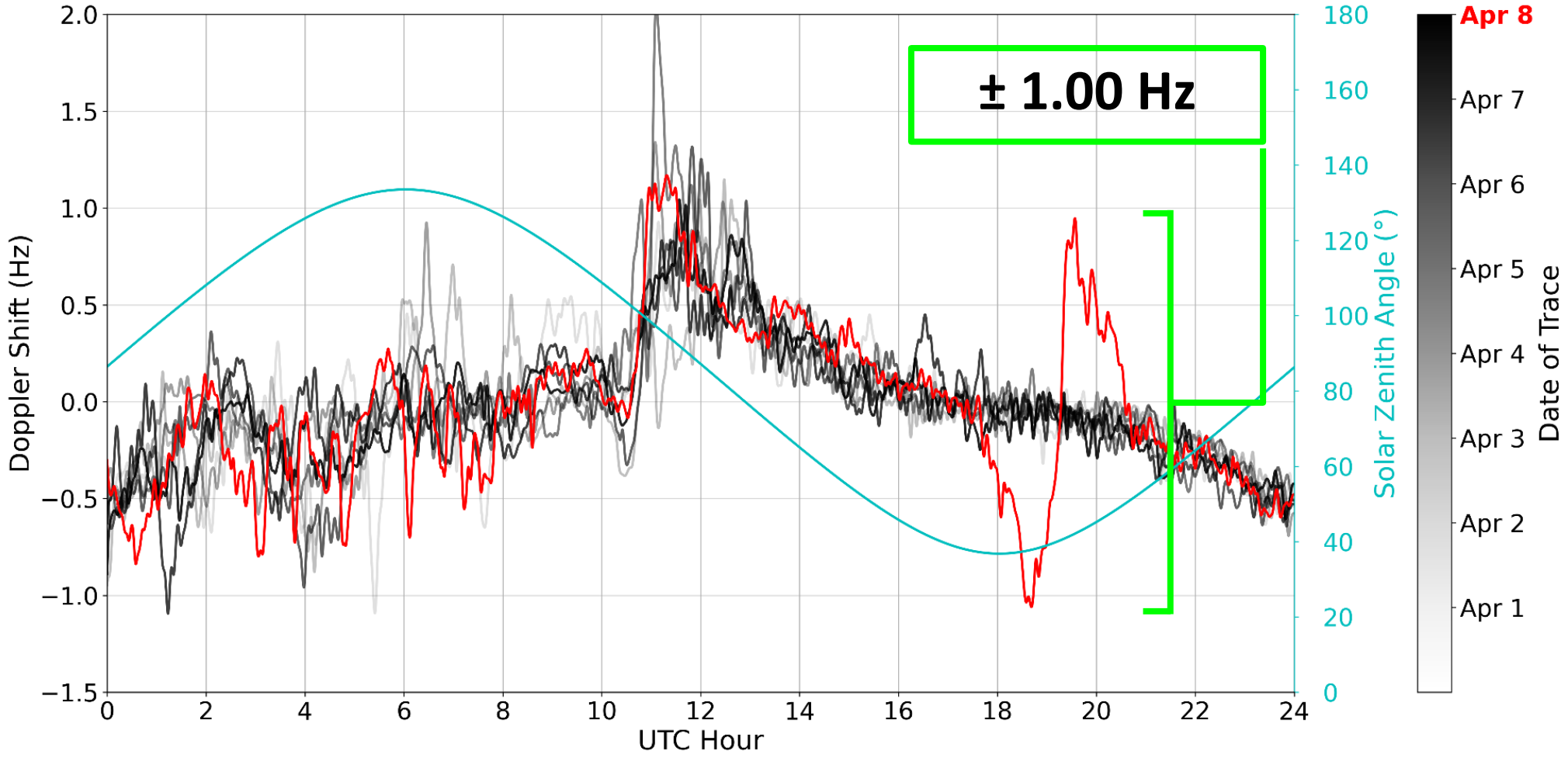
Case Studies

2024 Total Eclipse

Doppler Residuals of 7 Preceding Days + April 8, 2024 Trace



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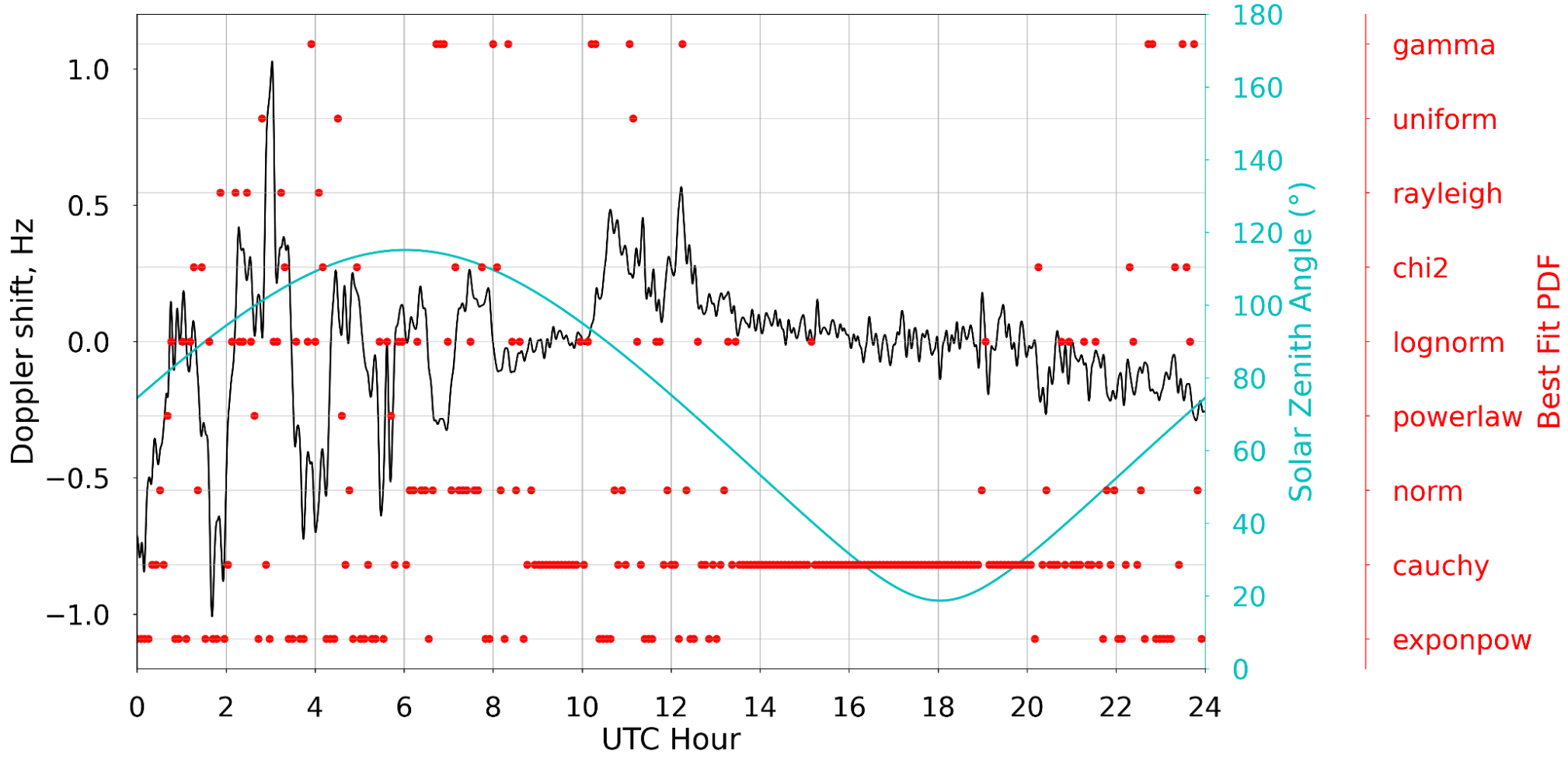
Statistical Analysis

July 1, 2021 Residuals + Best Fit PDFs for 5-minute Doppler Residual Bins



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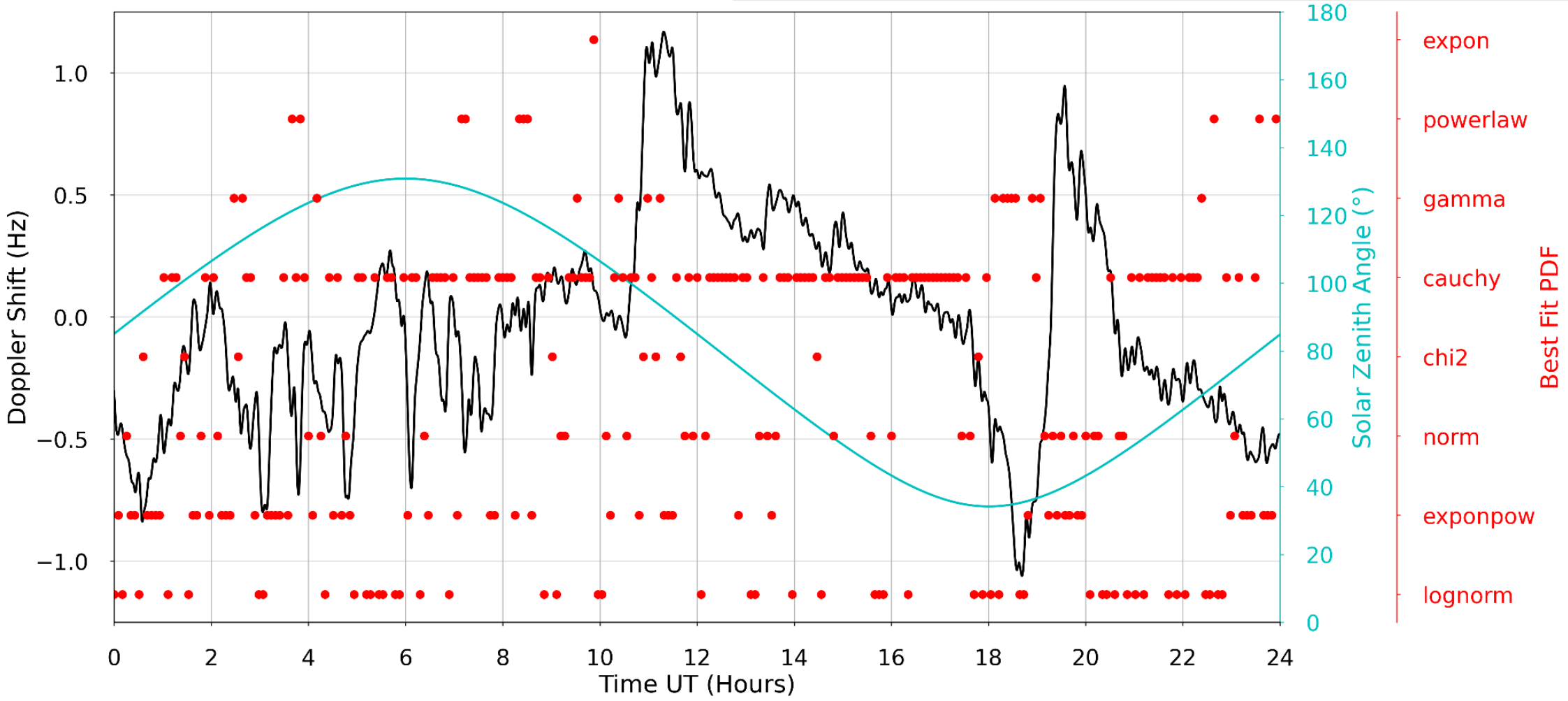
Statistical Analysis

April 8, 2024 Residuals + Best Fit PDFs for 5-minute Doppler Residual Bins



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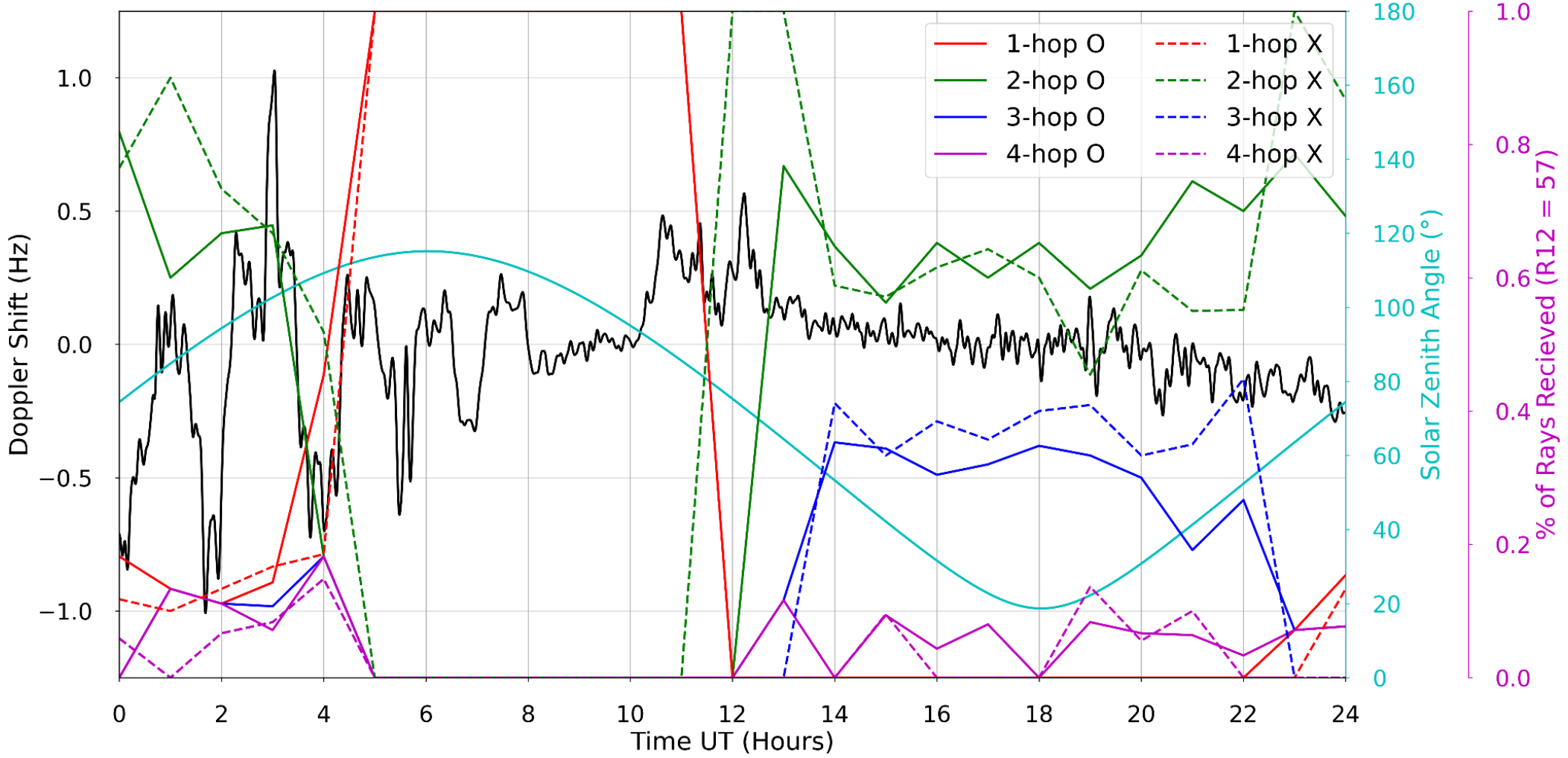
Signal Content

July 1, 2021 Doppler Residuals + Pharlap 3D Ray-tracing Summary



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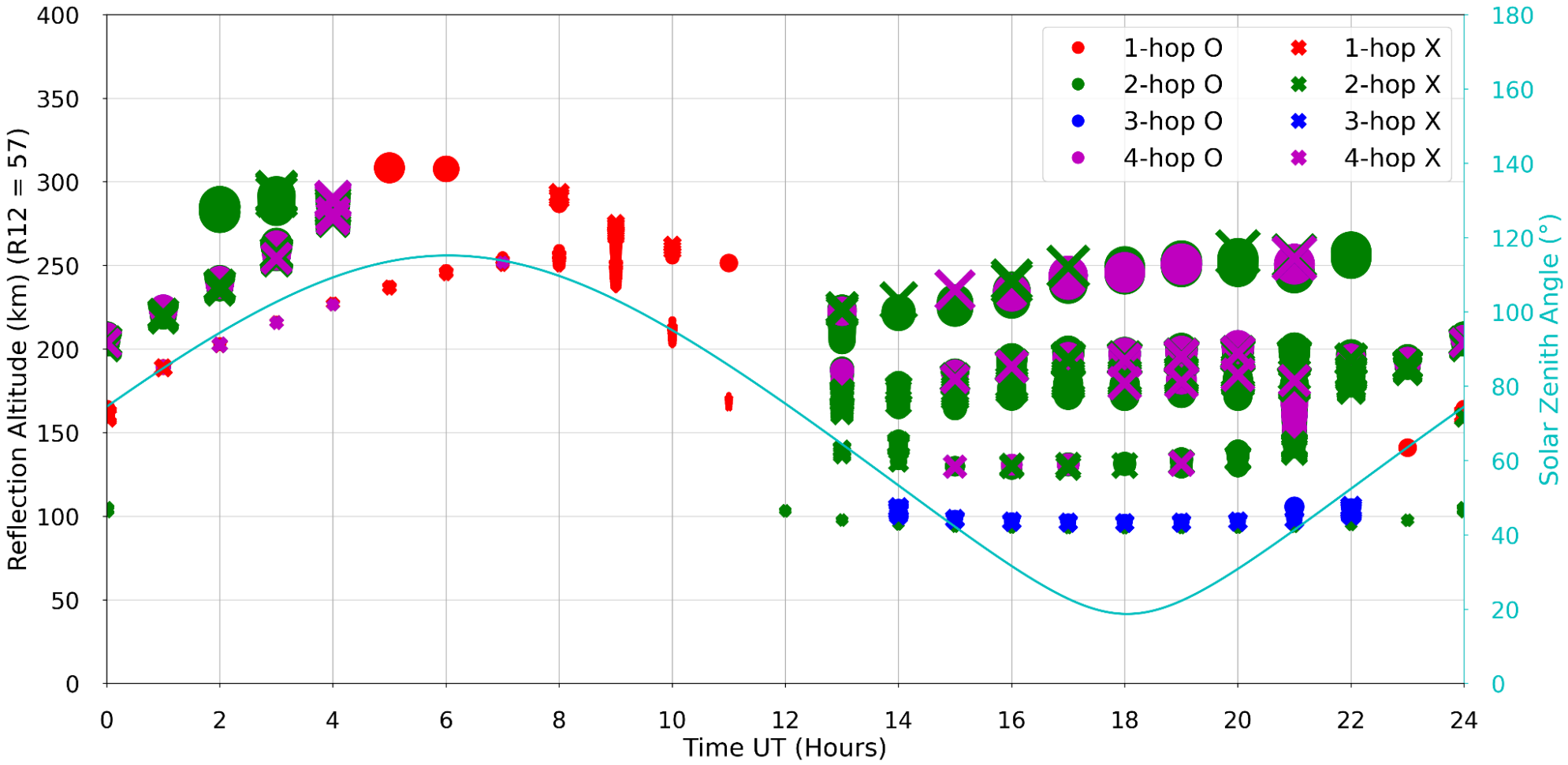
Discussion

Reflection Heights

Maximum Height for Pharlap 10 MHz Rays for Launch Angles of 0°-50°



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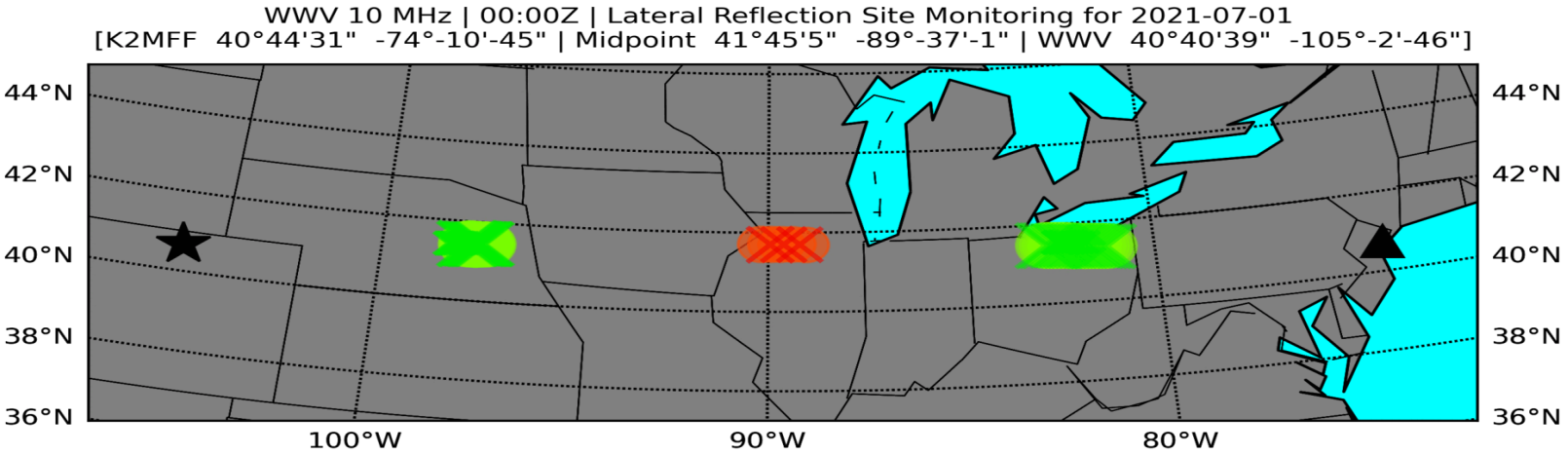
Discussion

Reflection Site Tracking

Geographic Location of Ionospheric Reflection Sites for 10 MHz Rays



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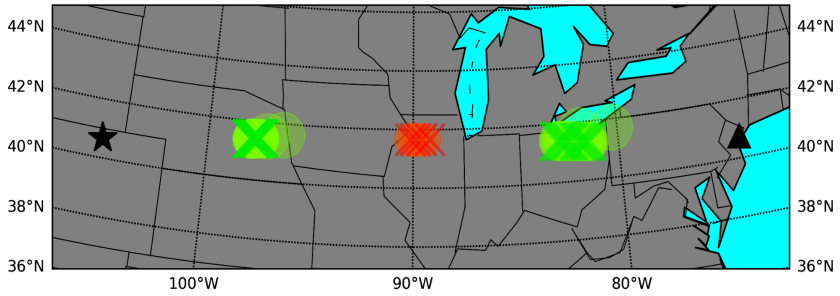

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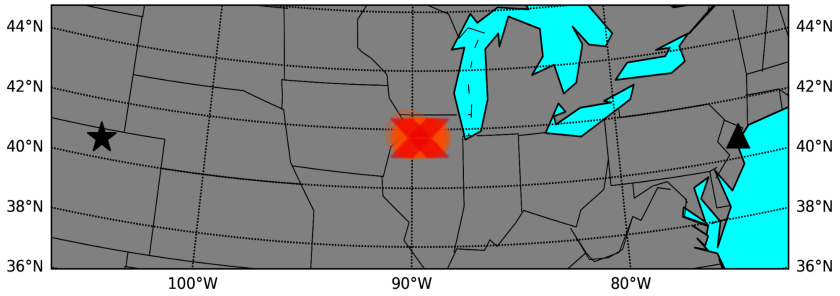

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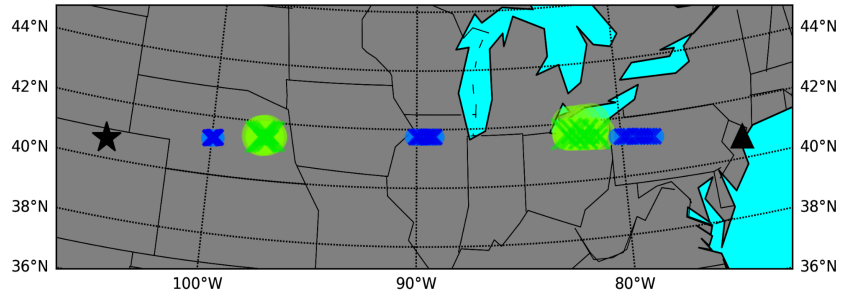

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Summary

1. The stability of daytime Doppler residuals is characterized by **Cauchy statistics**, while nighttime residuals exhibit a combination of **lognormal and exponential power** distributions

2. The behavior of daytime Doppler residuals is **entirely multi-hop** on this link
   a. Doppler residuals during the day represent a **superposition of variability effects** from geographically disparate reflection sites spread throughout the F-region

3. The signal between **05:00Z and 12:00Z** is entirely **1-hop**
   a. Doppler residual measurements **directly monitor** the variability of the **F2 ionosphere** at the reflection site

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References:

[1] Ionosphere. Space Weather Prediction Center. https://www.swpc.noaa.gov/phenomena/ionosphere
[2] K. Collins, A. Montare, N. Frissell and D. Kazdan, "Citizen Scientists Conduct Distributed Doppler Measurement for Ionospheric Remote Sensing," in IEEE Geoscience and Remote Sensing Letters, vol. 19, pp. 1-5, 2022, Art no. 3504605, doi: 10.1109/LGRS.2021.3063361.
[3] Collins, K., Gibbons, J., Frissell, N., Montare, A., Kazdan, D., Kalmbach, D., Swartz, D., Benedict, R., Romanek, V., Boedicker, R., Liles, W., Engelke, W., McGaw, D. G., Farmer, J., Mikitin, G., Hobart, J., Kavanagh, G., and Chakraborty, S.: Crowdsourced Doppler measurements of time standard stations demonstrating ionospheric variability, Earth Syst. Sci. Data, 15, 1403–1418, https://doi.org/10.5194/ essd-15-1403-2023, 2023.

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Thank you!

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